Optically Faint Microjansky Radio Sources

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ABSTRACT

We report on the identifications of radio sources from our survey of the Hubble Deep Field and the SSA13 fields, both of which comprise the deepest radio surveys to date at 1.4 GHz and 8.5 GHz respectively. About 80% of the microjansky radio sources are associated with moderate redshift starburst galaxies or AGNs within the I magnitude range of 17 to 24 with a median of I = 22 mag. Thirty-one (20%) of the radio sources are: 1) fainter than I >25 mag, with two objects in the HDF I_{AB} >28.5, 2) often identified with very red objects $I - K$ >4 , and 3) not significantly different in radio properties than the brighter objects. We suggest that most of these objects are associated with heavily obscured starburst galaxies with redshifts between 1 and 3. However, other mechanisms are discussed and cannot be ruled out with the present observations.

Subject headings: galaxies: evolution — galaxies: starburst, radio continuum

1. Introduction

We have recently completed a comprehensive radio survey of the Hubble Deep Field (HDF) region using the Very Large Array. Within a $40'$ region centered on the HDF we detected 40 sources at 8 GHz above 8 μJy and 371 sources at 1.4 GHz above 40 μJy (Richards et al. 1998, Richards 1999a). The angular resolution of the VLA observations ranged from 2-6$''$ and subsequent 1.4 GHz imaging with the Multi-Element Radio Linked Interferometer (MERLIN) increased the resolution to 0.2" (Muxlow et al. 1999; Richards 1999b).

Another deep radio survey conducted by our group (Windhorst et al., 1995; Kellermann et al. 1999) was centered on the Small Selected Area 13 field ($\alpha = 13^h 12^m 17.4^s$ and $\delta = +42^\circ\ 38'\ 05''$, J2000) and employed the VLA C and D configurations at 8.4 GHz producing a $6''$ beam. The rms noise in this image is 1.5 μJy with 39 radio source catalogued as part of a complete 5σ sample.

At the 10-100 μJy flux level, 60% of the radio sources are identified with bright (I $\sim$ 22 mag) disk galaxies (irregulars, peculiars, mergers), with typical redshifts of 0.2-1 (Richards et al. 1998). The diffuse, steep spectrum emission observed in these galaxy systems is interpreted as optically thin synchrotron radiation from coalesced supernovae remnants with perhaps a smaller fraction of bremsstrahlung radiation from HII regions. Some 20% of the microjansky radio sample are associated with low luminosity AGN (weak FR Is, Seyferts, and ellipticals).

The remaining 20% of the microjansky radio sources cannot be identified to optical magnitude limits of I = 25 mag. Three of these radio sources are contained in the Hubble Deep Field of which two remain unidentified at $I_{AB} > 28.5$ mag. In this Letter we list the sample of these radio sources associated with faint and/or red objects and discuss their possible nature.

2. Identification and Colors of Radio Sources

Optical photometry in the I and K bands were obtained in the HDF (Barger et al. 1999) and SSA13 fields (Cowie et al. 1996). First we aligned these wide field I and K band images under our radio detections with residual astrometric uncertainties of approximately $0.2''$. The absolute radio positions are known to 0.1-$0.2''$ rms in the HDF and 0.3-$0.6''$ rms in SSA13 and are tied to the standard FK5 inertial frame (Richards et al. 1998).

Using our astrometrically aligned optical images, we attempted to make identifications of the 111 (79 in the HDF, 32 in SSA13) radio sources contained within the I-band images which only partially cover the radio fields. These optical images have comparable depths of 24.8 mag and 25.0 mag (2 σ) in the Kron-Cousins system within the HDF and SSA13 fields, respectively. Identifications were chosen based on optical magnitude and the optical-radio angular separation as described in Richards et al. (1998). In most cases the radio emission lies directly on top of a bright galaxy and the association is unambiguous. For any identification reliability less than 10% , we classified as 'unidentified,'. The Hubble Space Telescope flanking field images were also checked for optical emission for each of these unidentified sources in the HDF region.

A magnitude histogram of the optical identifications is shown in Figure 1. Eighty-four secure identifications were found. Clearly, the bulk of the sample is identified with relatively bright (I $\lesssim$22 mag) galaxies. As can be seen from Figure 1, approximately 20% of the radio sources cannot be identified to I = 25 mag, although a few of the unidentified radio sources show faint optical emission below the formal completeness limit of the optical image.

We next used deep HK' images of the HDF (Barger et al. 1999) and SSA13 (Cowie et al. 1996) to estimate K magnitudes (K = HK' - 0.3 mag in the Johnson system) for our radio detections. I–K colors for the 84 optical identifications (heavy dots) are compared against the I–K colors of the field population (light dots; Barger et al. 1999) in Figure 2.

Two properties of the identifications of the 84 radio sources are clear from Figure 2: 1) For objects fainter than I > 21 mag, the galaxies associated with the identified radio sources are redder than the general field galaxy population at the same flux limit. 2) There is a monotonic trend for the optically fainter radio sources to have redder colors and reaches $I-K \simeq 3$ at I = 24 mag.

3. The Sample of Optically Faint and Red Radio Sources

Using the list of 111 radio objects with existing optical/near-infrared photometry , we isolated a sample of optically faint and/or red radio objects with I > 25 and/or $I-K>4$ (two magnitudes redder than the mean of the field galaxies in the HDF region; Barger et al. 1999). Table 1 presents the 31 optically faint/red objects along with radio flux density (measured at 1.4 GHz for the HDF sample, and 8.4 GHz for the SSA13 sample), statistical significance of the radio detection, radio spectral index for the HDF sample, and $I-K$ color. We show radio-optical overlays of the 17 radio sources contained in the HDF region in Figure 3. An additional red radio object in SSA13 is reported by Partridge, Eppley, and Spillar (1999).

Here we note distinctive properties of a few of the optically faint radio properties, including possible associations at other wavelengths. Another very red radio source listed in Table 1 (VLA J123642+621331) is described in a companion paper by Waddington et al. (1999).

VLA J123646+621226: Contained in the HDF (Williams et al. 1996) and the deep near-infrared observations of Thompson et al. (1999), places magnitude limits of I_{AB} >28.5, J_{110} >29, and H_{160} >29 mag for any counterpart. The radio emission is particularly diffuse and has a steep radio spectrum with $\alpha = 0.90$. VLA positions measured independently at

1.4 GHz and 8.5 GHz agree with 0.4″, consistent with their expected standard errors.

VLA J123651+621221: The higher resolution HDF frame clearly shows that this radio source is not associated with the foreground spiral to the south (Richards 1999c, fig. 1). Detected at $I_{AB} = 27.8$ mag in the HDF, this radio source is the second reddest optically selected object in the HDF-NICMOS survey of Dickinson et al. (1999) with $J_{110} - H_{160} = 1.6$. The sub-mm source HDF850.1 lies 5″ to the northeast (Hughes et al. 1998; Downes et al. 1999), which has been detected at 1.3 mm with subarcsec positional accuracy. The 1.3 mm source is coincident with the faint 8.5 GHz radio detection VLA J123651+621226 (Richards et al. 1998). However, the 1.3 mm image also shows a 3 σ detection within 1″ of the position of VLA J123651+621221, suggesting the sub-mm source HDF850.1 is a blend of two independent sources located in the 15″ JCMT/SCUBA beam.

VLA J123656+621207: This very steep spectrum radio source ($\alpha > 1.3$) lies within the HDF, placing a limit of $I_{AB} > 28.5$ mag on the counterpart. Deep near-infrared observations show no sign of emission at the position of the radio source to $J_{110} > 29$, $H_{160} > 25$, and K > 24 mag (Barger et al. 1999, Dickinson private communication 1999). The sub-mm source HDF850.2 lies 3″ to the southwest and is likely the same object as the radio source (Hughes et al. 1998; Barger, Cowie & Richards 1999).

VLA J123721+621130: A $I - K > 5.2$ object is identified with this inverted spectrum radio source. The radio emission is likely synchrotron self-absorbed from an optically obscured AGN. The optical galaxies to either side of the radio emission are probably unrelated.

4. Discussion and Conclusions

The radio properties of these 31 optically peculiar sources are not in themselves unusal. In general the radio sources are extended over a few arcseconds, have steep radio spectral indices, and are distributed over a range of flux density. Only the faintness of their optical counterparts sets them apart from the bulk of the microjansky radio population. We also note that the sources reported here are not variable on the time scales of days to months, over which our observations extended, ruling out association with variable AGN, gamma ray bursts, and supernovae.

We consider several possibilities for the nature of these radio sources in order of their likelihood:

1. High z-starbursts ($1 < z < 3$): Given that the majority of submillijansky radio sources are associated with star-forming galaxies, it is plausible that a tail of the parent galaxy population is so obscured by dust that only the radio emission is visible. In this case we would expect the radio emission to be steep spectrum and possibly resolved. The host systems would likely be disk galaxies, possibly merging or perturbed in analogy to the local ultraluminous IRAS galaxies. Beyond redshifts of 2-3, our sensitivity to star-forming galaxies cuts off due to our flux density limits. VLA J123651+621221 is a candidate dust enshrouded system.

2. Extreme redshift AGN ($z > 6$) - Another possibility, is that some of the radio sources with very faint optical fluxes are at extreme redshifts, where the Lyman 912Å break blanks out the I-band continuum, placing them at $z > 6$. With our present radio sensitivity, we could have detected a nominal FR I galaxy to $z \simeq 10$. It is interesting to note that the empirically determined $K - z$ relation observed for brighter radio galaxies implies redshifts greater than five for several of our radio sources (Dunlop & Peacock 1990) *if* they are FR I radio galaxies.

3. Moderate redshift ($z < 2$) AGN: Field elliptical galaxies and Seyferts often display evidence for a radio AGN component. However, typically the optical magnitudes of such systems are $L*$ or greater and thus to escape detection to I = 25, would place them at redshifts in excess of two. VLA J123721+621130 might be of this variety.

4. One sided radio jets: We cannot discount the possibility that some of the optically unidentified radio sources are the brightest jet of a nearby but displaced optical galaxy. In this case we would expect the parent galaxy to be a luminous elliptical containing an AGN. The radio emission in this case should be extended and steep spectrum. Radio source VLA J123646+621226 could possiblely fit in this category. However, FR Is comprise less than 5% of the submillijansky radio population and are usually solidly identified with bright galaxies at $z \lesssim 1$ (Kron et al. 1985).

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Figure Captions

Fig. 1.— I magnitude histogram of radio sources in the HDF and SSA13 regions. The mean of the distribution is I = 21.6 mag, with a median of I = 22.1 mag.

Fig. 2.— I–K color magnitude diagram for the identified radio sources in the HDF and SSA13 regions as shown as large solid dots. The smaller dots are the data from the field galaxy sample of Barger et al. (1999). The light broken line represents the mean I-K = 2.2 of the field galaxy sample. The solid line is a linear fit to the I-K colors of the radio identifications. The heavy broken line shows color-mag limits for I = 24 and K = 20 (HFF and SSA13 regions) and I = 24 and K = 23 (HDF region).

Fig. 3.— Radio-optical overlays of 17 optically faint radio objects isolated in the HDF region. The grey scale is from a log stretch of an I-band image of Barger et al. (1999) and the contours from a 1.4 GHz VLA images of Richards (1999a). The radio resolution is approximately $2''$ and contours are drawn at the -2, 2, 4, 8, 16, 32 and 64 σ level (σ = 7.5 μJy). The images are oriented with north to the top and east to the left and are $20''$ on a side.

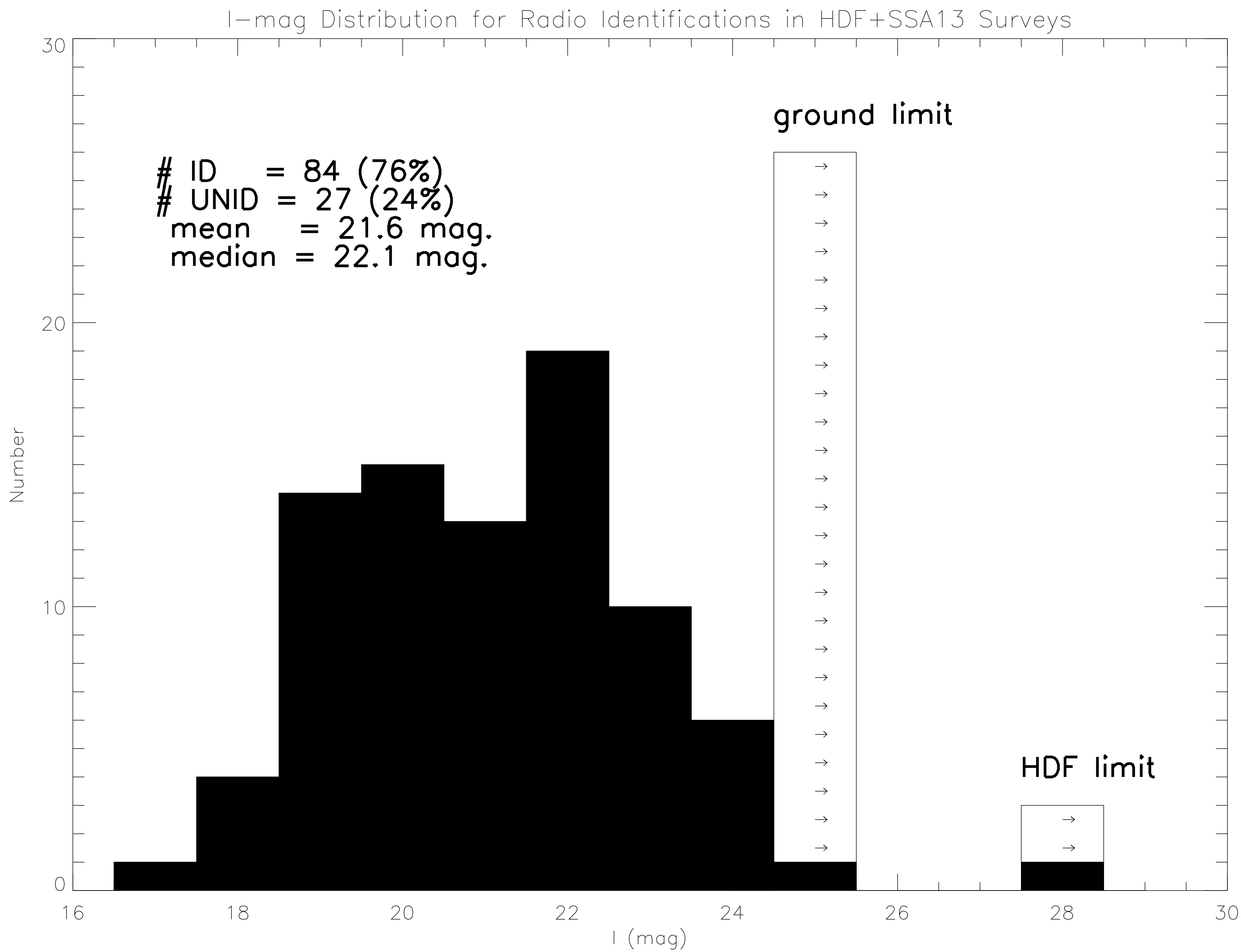
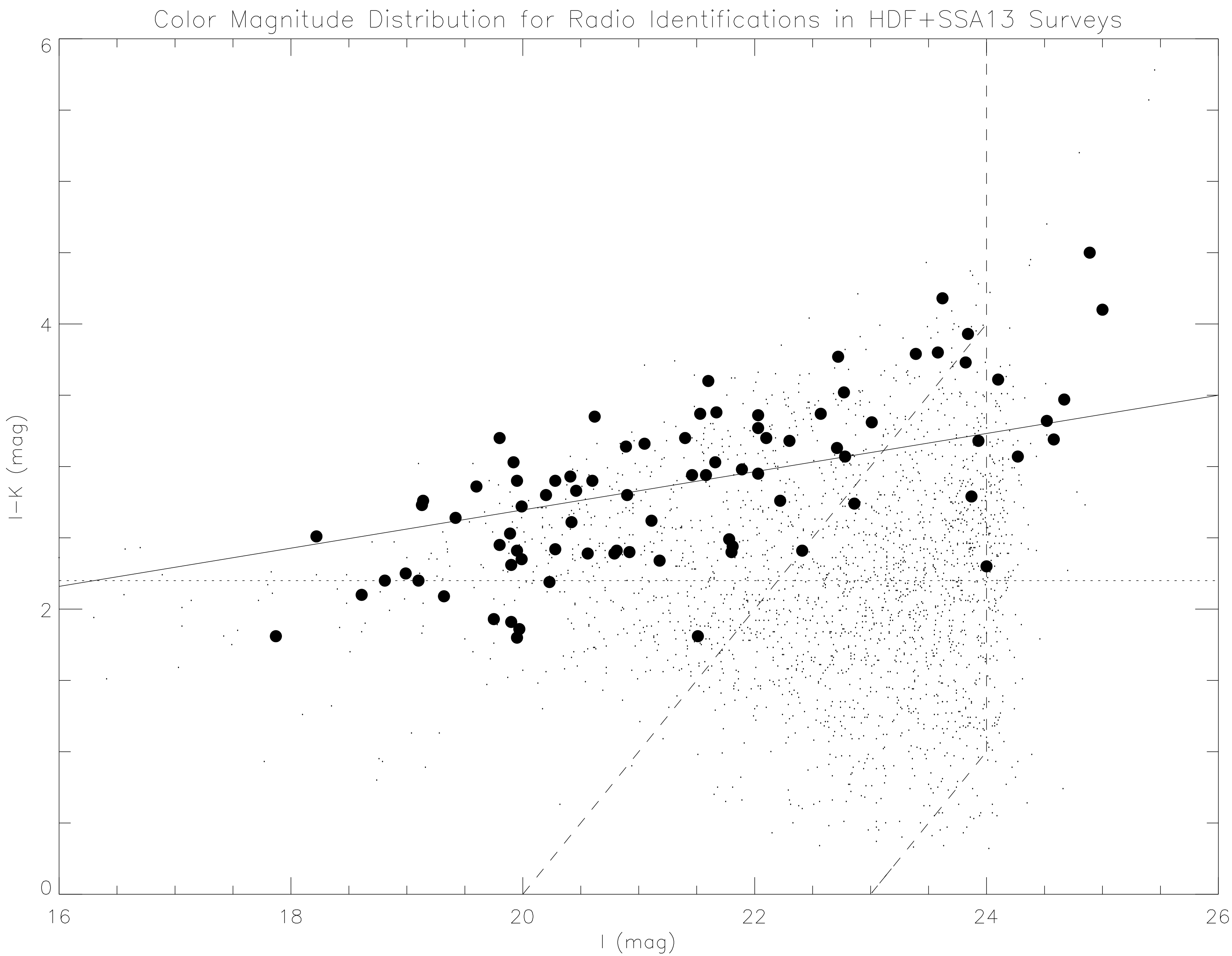
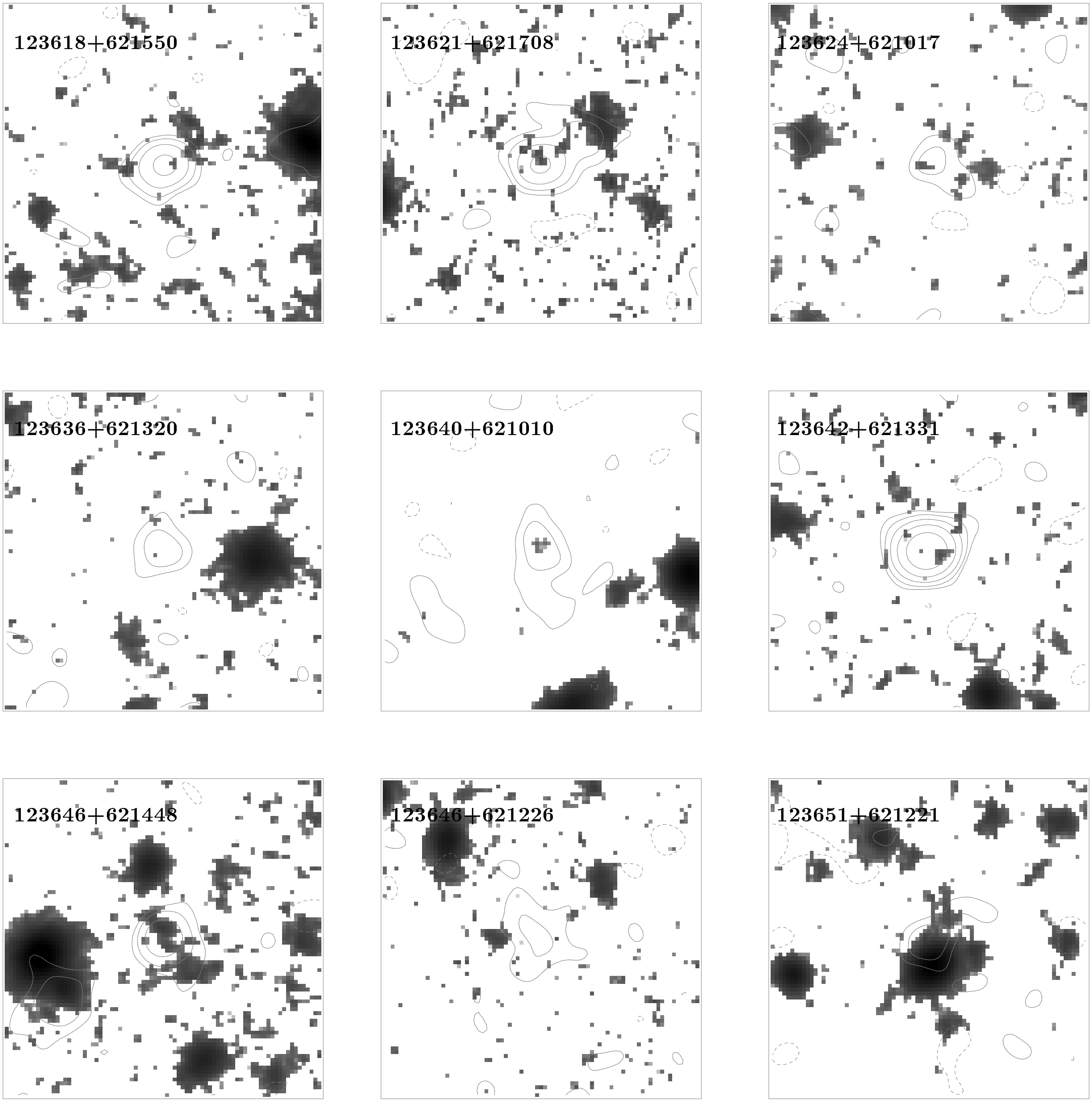

I–mag Distribution for Radio Identifications in HDF+SSA13 Surveys
# ID = 84 (76%)
# UNID = 27 (24%)
mean = 21.6 mag.
median = 22.1 mag.
ground limit
HDF limit
Number
0
10
20
30
I (mag)
16
18
20
22
24
26
28
30

Table 1: Optically Faint Objects in the HDF+SSA13 Radio Surveys

Name	R.A. (hh mm ss)	DEC (° ′ ″)	$\mathbf{S_{1.4GHz}}$ (μJy)	SNR	α	I	$I-K$
VLA J123618+621550	12 36 18.328±0.016	62 15 50.48±0.11	150	18	>0.63	>25	–
VLA J123621+621708	12 36 21.272 0.016	62 17 08.40 0.11	150	17	>0.56	>25	–
VLA J123624+621017	12 36 24.278 0.024	62 10 17.01 0.17	54	6.5	>0.37	>25	–
VLA J123636+621320	12 36 36.907 0.022	62 13 20.35 0.15	50	6.6	>0.90	>25	–
VLA J123640+621010	12 36 40.735 0.026	62 10 10.55 0.18	87	11	0.44	>25	–
VLA J123642+621331	12 36 42.098 0.015	62 13 31.42 0.10	470	68	0.94	>25	>3.7
VLA J123646+621448	12 36 46.049 0.017	62 14 48.69 0.12	120	13	0.84	>25	–
VLA J123646+621226	12 36 46.698 0.027	62 12 26.54 0.19	72	7.1	0.90	>25	–
VLA J123651+621221	12 36 51.760 0.027	62 12 21.30 0.19	49	8.3	0.71	>25	–
VLA J123654+621039	12 36 54.703 0.023	62 10 39.62 0.16	48	6.3	>1.00	>25	–
VLA J123656+621207	12 36 56.605 0.027	62 12 07.62 0.19	46	5.5	>1.32	>25	–
VLA J123700+620909	12 37 00.256 0.015	62 09 09.75 0.10	320	40	0.89	>25	–
VLA J123701+621146	12 37 01.574 0.020	62 11 46.62 0.14	130	12	0.67	>25	> 5.0
VLA J123707+621408	12 37 07.208 0.027	62 14 08.08 0.19	45	7.8	0.29	24.7	4.5
VLA J123707+621121	12 37 07.974 0.023	62 11 21.54 0.16	60	8.2	>0.82	>25	–
VLA J123711+621325	12 37 11.977 0.025	62 13 25.73 0.17	54	6.5	>1.16	>25	–
VLA J123721+621130	12 37 21.251 0.016	62 11 30.02 0.11	380	72	–0.28	>25	>5.2
VLA J131202+423751	13 12 02.79±0.04	42 37 51.4±0.5	29	6.0	–	>25	–
VLA J131205+423852	13 12 05.61 0.05	42 38 52.0 0.6	14	4.8	–	25.0	4.1
VLA J131207+424013	13 12 07.14 0.04	42 40 13.3 0.5	30	5.7	–	>25	>3.5
VLA J121213+424120	13 12 13.43 0.04	42 41 20.0 0.4	43	8.4	–	>25	–
VLA J131214+423823	13 12 14.44 0.05	42 38 23.7 0.5	8.9	6.7	–	>25	>3.3
VLA J131214+423731	13 12 14.51 0.05	42 37 31.1 0.5	8.8	5.8	–	>25	>4.9
VLA J131216+423921	13 12 16.07 0.02	42 39 21.5 0.2	34	16	–	>25	–
VLA J131217+423930	13 12 17.61 0.04	42 39 30.6 0.4	15	8.1	–	>25	>4.1
VLA J131219+423831	13 12 19.83 0.04	42 38 31.3 0.5	18	5.6	–	>25	>3.5
VLA J131220+423923	13 12 20.02 0.04	42 39 23.7 0.4	14	7.9	–	>25	–
VLA J131220+423703	13 12 20.16 0.04	42 37 03.9 0.4	14	8.0	–	>25	>4.5
VLA J131220+424029	13 12 20.19 0.04	42 40 29.7 0.3	41	11	–	>25	>4.0
VLA J131225+423656	13 12 25.22 0.04	42 36 56.5 0.5	12	5.8	–	>25	>3.5
VLA J131232+424038	13 12 32.77 0.01	42 40 38.3 0.1	180	22	–	23.6	4.2


Color Magnitude Distribution for Radio Identifications in HDF+SSA13 Surveys
I-K (mag)
I (mag)
0
2
4
6
16
18
20
22
24
26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123621+621708
123624+621017
123636+621320
123640+621010
123642+621331
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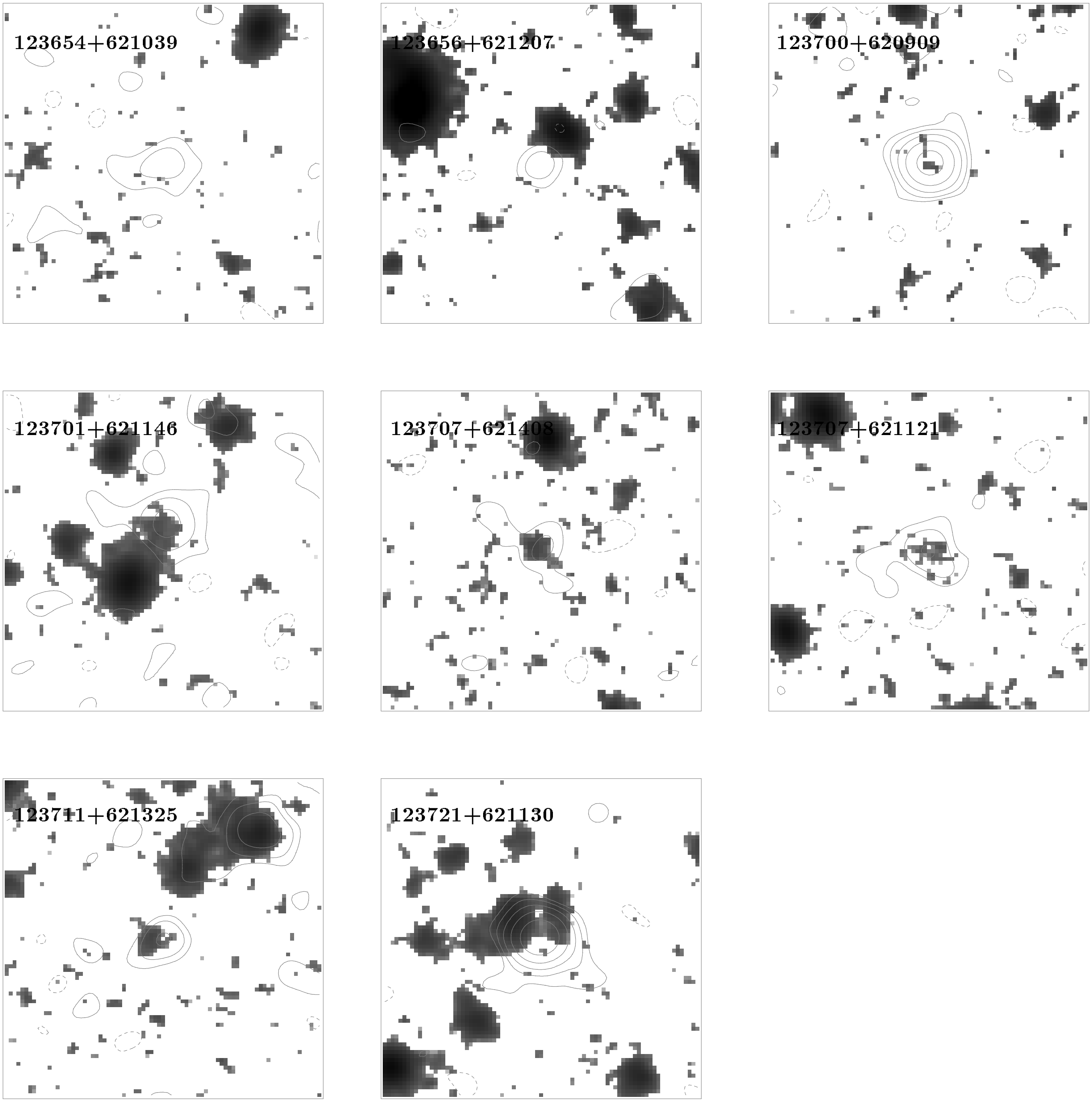
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123656+621207
123700+620909
123701+621146
123707+621408
123707+621121
123711+621325
123721+621130